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CLIMATE MODIFICATION AND NATIONAL SECURITY

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The climate of the earth has not always been as it is now. Geologic records indicate that there have been long periods of quasi-stable climates that are different from what we know today. There is every reason to believe that changes could occur in the future. Our knowledge of what caused the past variances in climate is very sketchy and we do not have a well-developed methodology for anticipating future changes. There may be natural events -- changes in the output energy of the sun, changes in the form and shape of the oceans and continents on the earth -- which could cause changes in the climate. But there are also possibilities that the activities of man will change the climate.

At one time, not too long ago, we could speak rather glibly of man versus nature, and talk about "natural" events and "manmade" events. We had some rather strong ideas that there was a great difference in that things were either "natural" or "manmade." But the explosive growth of the human population and its growing use of energy has made this kind of distinction difficult to take seriously in this day and age. Man is having a very definite influence on not only his local surroundings, but the whole nature of the planet. Man is part of nature and his activities are very likely to influence the future course of the natural environment of the earth. Many of man's works result in deleterious effects on the environment.

Most such changes are likely to be inadvertent. The desire for more power and energy may cause man to use fossil fuels to produce heat, to produce waste, and this might influence the climate of the earth.

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Actions to alter the face of the earth in some major way for some beneficial purpose could alter the climate of the earth in a harmful way. The important point is, that today we have the technology and the available energy to make vast changes in the face of the globe and the composition of the atmosphere. These changes could very well affect the climate in which we live. Finally, we must not overlook the small, but finite, possibility that deliberate attempts might be made to alter the climate of the world to the detriment of the United States. I do not think this is a very likely situation, but it is a possibility. I think the more likely threat to our national security is the possibility that changes will be made to improve a bad situation somewhere in the world that might have a deleterious effect on the climate of the United States.

The question then arises, if we are really concerned about the possibility that man might affect the climate of the earth, what can we do about it? What are the problems? What are the possible solutions? How should we proceed to look at the problems of the possibility of climatic change? One approach, of course, is to try to look into the past and try to discern from geological records what climatic changes occurred, and deduce the causes of such climatic regime. This is a very difficult task. There have been some minor climatic fluctuations in the recorded past, but long records are not quantitative and we have only gross qualitative descriptions of what happened. There is very little information on possible causes, so our study of past climates can only be an attempt to define them more precisely, and then to speculate on the causes.

Another method which has been proposed to study the climate is by means of numerical simulation. The concept of numerical prediction, which was first raised by Richardson fifty years ago, has been developed to a high degree. There are certain problems of numerical prediction which are well in hand, and you have heard quite a bit about some of these at this conference. All of the numerical prediction methods, however, run into the difficulty of the predictability problem which has been discussed so well by Ed Lorenz.

Lorenz advances the proposition that "...certain formally deterministic fluid systems which possess many scales of motion are ob-

servationally indistinguishable from indeterministic systems; specifically, that two states of the system differing initially by a small 'observational error' will evolve into two states differing as greatly as randomly chosen states within a finite time interval...".[1] He goes on to demonstrate and quantify this proposition for a simple model which has no forcing functions and no dissipation. This type of error amplification has been demonstrated by the exercise of other models.[2] We are not so much concerned with this type of error as we are with the ability of the model to discriminate between the ensembles from which the randomly chosen states are selected. Thus we have set about to determine the changes in the mean state of a model of the atmosphere with different boundary conditions and different initial conditions. Our preliminary results indicate that the mean circulation for a period 30 to 60 days after the ice was removed from the Arctic Ocean was significantly different from the runs with the ice present. We have not, as yet, explored the impact of this change on the climate.

A great many problems of numerical simulations are well under control. The work of the Geophysical Fluid Dynamics Lab, ESSA,[3] is an outstanding example of the fidelity with which numerical models can be made to represent the way the real atmosphere behaves. The basic problems of numerical integrations on the sphere have essentially been solved. There are other problems that have not been solved. There are problems of scale, problems of the resolution with which we can calculate in order to determine the effect of small-scale motions on the general circulation. There are also problems of physical processes for which we do not have a thorough understanding. And so, although we believe at the present time we have numerical models which are sufficiently realistic to be able to reproduce the climatic features we observe today, we cannot assume, a priori, that these models are sufficiently accurate to properly reflect changes which might alter the climate. We therefore have a twofold problem. One is to exercise the models we do have, and the other is to improve the models.

In the process of exercising the models we do have, what we are essentially doing, is asking the question, What changes in climate would result from the successful completion of a large project? I have already

alluded to the effect of removing the ice from the Arctic Ocean. There have been many speculations that, if one did this the ice would not return, or at least not very rapidly, and that the climate could be drastically altered.[4] There is serious talk of some large hydrologic projects -- changing the course of rivers, creating lakes where there are now deserts. We would like to estimate the effect this kind of operation would have on the climate. What might happen if some of the large ocean currents were diverted? What would result if films were developed to retard the evaporation of water over large ocean areas? Some of these projects might be undertaken with a very definite beneficial end in mind, and result in serious climatic problems. On the other hand, it is not inconceivable that, if a scheme were available which could change the climate, it might be used in a malicious fashion.

So finally, what is our approach to this whole problem of climatic simulation for national security? We want to find out primarily what changes in the face of the earth or in the content of the atmosphere would have an effect on the climate. We approach this problem by trying to exercise numerical models where the simple insertion of a few statements in numerical programs changes the face of the earth or the content or the condition of the atmosphere, and then look to see what the resulting change in the circulation would be. I've already alluded to the fact that our models are really not tuned finely enough so that we can be sure that the changes we see are actually the changes that would occur. Some of our parametric representations of certain processes might, under the new situation, be inadequate, and we could get the wrong result. This is an open question -- one which we are addressing first in our program at Rand.

With the numerical models now in use we are faced with another serious dilemma. They are run for several months to determine the change. Obviously, climate is not determined by several months. What one really wants to do is look at years. With our present generation of computing machines the time and expense to run for many years is just too great -- we do not have computing power to run current step-by-step integrations for long periods of time. There are two ways out of this dilemma. One is to build bigger and better computing machines. ARPA

has funded the development of ILLIAC IV, which will be used to try to make long runs of a step-by-step integration of the numerical model. We at Rand are trying to be ready with the programming and the model. We want to be ready to go on ILLIAC IV with this kind of numerical simulation as soon as ILLIAC IV is operating.

But there is another way of looking at this problem which will require more study and more finesse, and that is to try to find ways where we can simulate the gross climatic features without doing the step-by-step, day-by-day weather prediction. There are a good many people interested in this and several approaches to this problem. One way is through use of harmonic analysis[5] -- that is to try to filter out the small scale from the large scale and try to learn how to get the really gross effects without detailed study of the smaller scale. Another is the simple sort of zonal averaging such as MacCracken[6] has produced. It is a rather detailed computation scheme, but it works on a zonally averaged two-dimensional model of the atmosphere. There are difficulties with all these schemes, but we believe that all conceivable approaches must be pursued.

The Rand program in climate dynamics has been underway for about one year. It is at present divided into nine subprojects. The first project we undertook was to try to determine whether or not the predictability problem that Lorenz has raised would hamper our approach. We have made quite a few runs with the Mintz-Arakawa[7] 2-level model, changing the boundary conditions by running with present conditions and then taking the ice out of the Arctic basin. We have repeated these runs with randomly distributed temperature errors in order to discover whether the mean changes were discernible through the errors introduced by the randomly changed temperatures. The results of this are just beginning to come in and they indicate that indeed the mean circulation has been changed and that the random errors do not obscure the changes in the mean conditions. This work should be finished within the next 6 to 8 months with a rather complete report on our findings.

In the second project we are continuing with many other global circulation model experiments in which we will not necessarily worry about the statistical validations but will simply assume that the changes

shown by the model indicate the direction of the change. At present these are being run with the Mintz-Arakawa 2-level global circulation model with a 4x5-degree grid resolution. One experiment which has been run is the removal of the cold Eastern Tropical Pacific surface waters to compare with the work of Bjerknes.[8] Arakawa and Mintz are in the process of completing a 3-level model, the third level being a boundary layer and it is believed that this will greatly increase the fidelity of the model. We are also looking to the possibility of going to a much finer resolution than these experiments. In the meantime until the 3-level model is ready, we will continue with the 2-level model and make changes which have been suggested that might alter the climate.

The third project is on ocean models. One of the big deficiencies of the Mintz-Arakawa model, indeed most of the global circulation models, is that the ocean is not allowed to react in the same way that the atmosphere is. We have developed a barotropic ocean model which has been tested and reported on. We are in the process now of running this barotropic model for the world ocean. At the same time we have done some research and made some analyses to devise a baroclinic model with relatively few layers. This, we hope to mate with the Arakawa-Mintz 3-level model in order to produce a model which will allow the ocean to change with the changing atmosphere and the atmosphere to react to the changing ocean.

The fourth project is a study of the effect on atmospheric radiation of turbidity and cloudiness. This is an area where the theoretical background is not sufficient to make a really good parameterization of the effects on the atmosphere. We have not gone deeply into this as yet. It is at present in the study stage and we hope within a year to get some positive results for correcting some of the possible deficiencies in the current model.

Our fifth project deals with the smaller-scale convective cloud model. One of the great problems of global modeling is the inclusion of suitably parameterized models of small-scale convection. The fine grid which we hope to achieve should resolve synoptic scale disturbances, but below that there is not much hope that we can resolve such things as convective clouds. Since they are so important in redistributing

heat and moisture in the vertical, we are carrying out an experiment on model of cumulus convection in order to try to learn more about the heat and moisture transport by convective clouds. We hope eventually to develop a 3-dimensional model so that we will also be able to look at the effect of the transport of momentum by convective clouds.

Our sixth project is on numerical methods. We note that since the beginning of numerical weather prediction the approach to numerically integrating the equations of motion has been a series of finite-difference schemes. These have been developed to a high degree but the whole problem of numerical analysis remains something of an art and not completely developed to a science. A new method which instead of using finite differences uses a curve-fitting approach and then solves the curve-fit equation explicitly. It is known as Galerkin's method, it is complex, and we do not know whether it would provide any advantage over the current method but we're looking at it and we hope in a year to have a report on the possible utility of this method.

I mentioned earlier that the full-scale model even one as simple as the Mintz-Arakawa model uses a tremendous amount of time to step along in short time steps to produce results for the order of months or years. Our seventh project is to look at other approaches. At present the interest is centered on the zonally average model developed by MacCracken at LRL. We have programmed this. We are comparing it with the Mintz-Arakawa model. We are studying it for possible improvement and we'll decide very soon whether such an approach to very long term climatic models is feasible.

Our eighth project continues with the study of climate as it has been recorded or deduced. We believe that one of the ways we can bolster our confidence in a numerical solution is to try to reproduce some of the climatic changes that have occurred in the past. In order to do this we must, of course, know what changes have occurred and have some way of describing what we think caused these changes. As we develope theories of climatic change we will try them on numerical modeling. If, indeed, our proposed suggestions for why the climatic change occurred produce what we think happened, then we will have additional confidence in our method of numerical solution.

And finally, we are preparing to use the ILLIAC IV as soon as somebody throws the switch. We have already completed a programming of the cumulus cloud model developed by Murray. We chose this as a checkout program because this model has been programmed for many versions of many different machines and it will provide a measure of what we can expect from the ILLIAC IV. Moreover, the kind of mathematics that are used in the convective cloud model and the number of grid points is very similar to what we would have in a global circulation model. Since the cloud model has already been checked out and ready to go, we are going to turn our programmers to the job of programming the Mintz-Arakawa model. We believe that as soon as a good documentation is available that we can turn our programmers loose, and that when the 3-level model comes along there will be no difficulty in converting to the 3-level model.

So those nine projects make up the Rand program. It is not complete. You will note that we do not have a project on the harmonic analysis approach to long-term climate. Perhaps that will come, but we believe that there are others in the country who are perhaps more capable than we to proceed with that. You will note that there are many small scale features that we have not addressed. We have no work going on at Rand in transfer of heat and momentum and energy from the surface of the earth into the atmosphere. We believe this is important but again we think there is competence elsewhere in the country that could be turned to these problems.

The Rand program on climate dynamics for environmental security starts with the concept that the U.S. might be harmed either inadvertently or maliciously by changes in the climate, so that we must find out how to anticipate change in the climate. There is much work to be done to develop a methodology and an estimate as to how the climate might change or be changed.

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